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DEPARTMENT OF COMMERCE
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AN OUTLINE OF TROPICAL WEATHER SYSTEMS

Robert Grebe

National Weather Service Training Center
Kansas City, Missouri

January, 1983

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DEDICATED

to the memory of

BILLY LEWIS
(1927 - 1980)

his pioneering vision into mesoscale hurricane features provided the spark for the research fire that now burns brightly.

ACKNOWLEDGMENTS

The author specifically wishes to express his sincere appreciation for the cricital review and valuable comments of:

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One of the most challenging storms to cope with is the landfalling hurricane. Buildings begin to look like Hollywood stage props and your elevation seems to sink below sea level. Dan Rather media look-alikes descend upon your Weather Office with "*catastrophe*" reflecting from the lenses of their tinted glasses. Some of the people left in your county warning areas are moving as if in a dream and the stress of the event brings out their best and worst.

The world is temporarily topsy-turvy.

Against this background, I have seen you perform superbly and wish to be counted amongst your supporters. This is offered with the hope that one or two items will make your next cyclone a little easier.

Robert Grebe
September 1982

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TABLE OF CONTENTS

APPENDICES

AN OUTLINE OF TROPICAL WEATHER SYSTEMS IN THE NORTH ATLANTIC, CARIBBEAN, GULF OF MEXICO AND EASTERN NORTH PACIFIC.

TROPICAL DISTURBANCES

Definition: A discrete system of apparently organized convection originating in the tropics or subtropics, having a non-frontal migratory character, and maintaining its identity for 24 hours or more.

A tropical disturbance is typically identified by a convective appearance on satellite pictures and is associated with a perturbed wind field.

I. Frequency

Simpson (1980) uses the term "seedling" for a tropical disturbance and notes that about 100 seedlings originate in Africa, the North Atlantic, Caribbean and Gulf of Mexico each year. Most form over the African Continent. Frank and Clark (1979) noted that the average number of seedlings for the ten year period (1968-77) was 104 with a minimum of 85 and a maximum of 113 for the same period.

II. Synoptic Patterns Favorable For Formation

A. Tropical Waves

Definition: A trough or cyclonic curvature maximum in the trade wind easterlies.

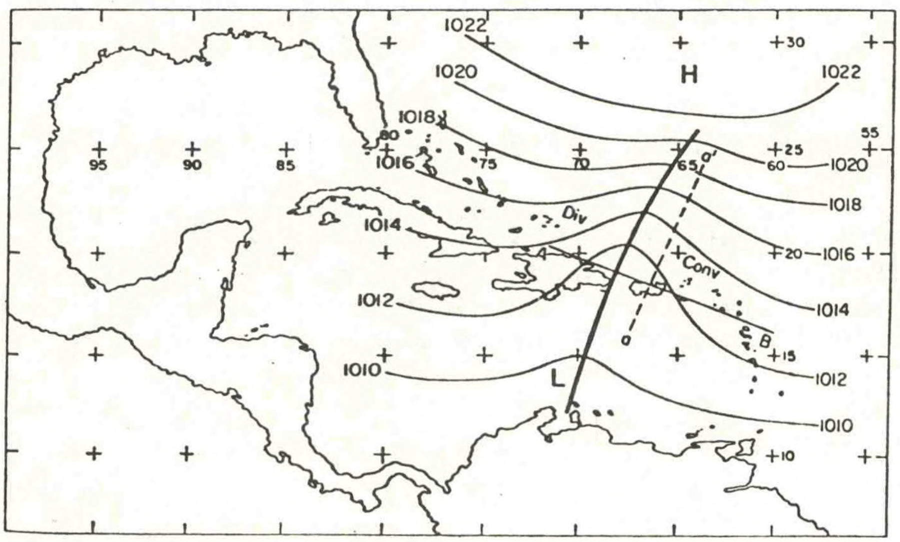

Fig. 1. Model of waves in the easterlies: surface chart. (After Riehl, 1954)

1. Evolution

Most seedlings are tropical waves. Burpee (1972) stated that most waves originate as an instability of the easterly flow near 10°N in eastern or central Africa. They have a typical period of 3-4 days and a wavelength of 2500 km (1350 nmi). Tropical waves travel westward 7-8 m/s (16-18 mi/hr) and cross the Atlantic in the easterly tradewinds. Many tropical waves have been traced beyond the Caribbean to the eastern North Pacific.

A few waves propagate westward along the intertropical convergence zone (ITCZ) and can be followed with satellite images. Relatively little is known about the origin or structure of these waves.

2. Frequency

An annual average of 64 tropical waves were detected in the Atlantic during the ten-year period from 1970-1979. The number of waves ranged from a maximum of 76 to a minimum of 51 during the same ten year period.

3. Associated Weather

In western Africa and the eastern Atlantic, cloudiness and convection is to the west of the wave axis. In the western Atlantic, the low-level pattern for a tropical wave is one of suppressed cloud development, sinking air and divergence ahead of the wave axis. Convergence, convective clouds and showers are typical of the wave axis eastward.

B. Intertropical Convergence Zone Disturbances

About one fourth of all tropical disturbances from 1970-1979 originated in the ITCZ. Weakly developed lows in the ITCZ do not attain significant pressure falls near the equator and must be north of 5°N to develop complete cyclonic circulation.

C. Upper Tropospheric Cold Lows and Troughs

A few seedlings result from cold lows cutting off near 200 millibars and upper troughs extending from the subtropics towards the tropics. According to Pelissier (1981), about 14% of the cutoff lows develop near Cape Hatteras and can persist up to two weeks.

D. Old Polar Fronts

The remnants of polar fronts can become lines of convection. Pelissier (1981) noted that it is not uncommon for these shear lines to develop disturbed areas early and late in the season in the Caribbean Sea and Gulf of Mexico.

TROPICAL CYCLONES

Definition: A nonfrontal, low pressure system of synoptic scale, developing over tropical or subtropical waters and having a definite organized circulation.

The terms tropical depression, tropical storm or hurricane are subclassifications of the more general term *"tropical cyclone"* and are dependent upon the sped of sustained (one minute average) counterclockwise winds near the center.

I. Favorable Areas of Formation

During the course of the hurricane season, many North Atlantic tropical cyclones classically develop from tropical waves moving off the coast of Africa. Neumann et al. (1978) described early season tropical cyclones as being almost exclusively confined to the western Caribbean and the Gulf of Mexico.

By the end of June or early July, the area of formation gradually shifts eastward and continues eastward to late July.

By late August, formation is over a broad area which extends eastward to near the Cape Verde Islands. "Cape Verde" type storms are most frequent from the latter part of August to mid-September and often traverse the entire Atlantic Ocean.

The area of formation retreats westward in mid-September and returns to the western Caribbean by early October.

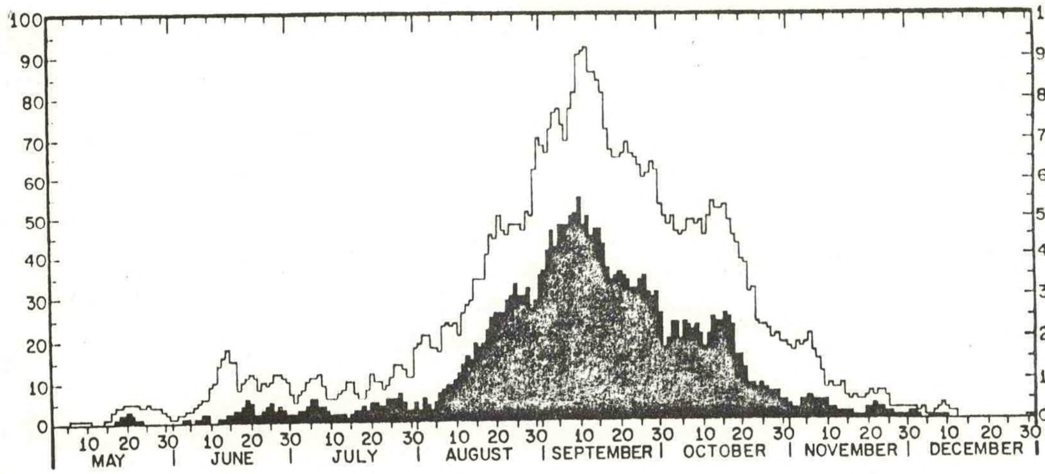

Fig. 2. Number of tropical storms and hurricanes (open bar) and hurricanes (solid bar) observed on each day, May 1 - December 30, 1886-1977. (After Neumann et al., 1978)

TABLE 1 PRINCIPAL AREAS OF TROPICAL CYCLONE FORMATION IN THE TROPICAL NORTH ATLANTIC (AFTER RIEHL, 1979)

AREA	SEASON
EAST OF LESSER ANTILLES	JULY-EARLY OCTOBER
CARIBBEAN EAST OF 70°W	JULY-EARLY OCTOBER
NORTH OF WEST INDIES	JUNE-OCTOBER
WEST CARIBBEAN	JUNE, LATE SEPTEMBER-EARLY NOVEMBER
GULF OF MEXICO	JUNE-NOVEMBER

TABLE 2 TROPICAL CYCLONE FORMATION IN THE EASTERN NORTH PACIFIC (AFTER RIEHL, 1979)

AREA	
OFF THE WEST COAST OF CENTRAL AMERICA	JUNE-OCTOBER

II. Tropical Depression

Definition: A tropical cyclone in which the maximum sustained surface wind (one minute average) is 33 knots (38 mi/hr) or less. Tropical depressions are characterized by having one or more closed isobars.

A. Evolution

Many tropical depressions will originate as large disorganized circulation centers within areas of disturbed weather. These systems generally intensify slowly and may even dissipate before reaching tropical storm intensity.

More rarely, depressions will form small circulation centers that intensify rapidly and are more likely to reach tropical storm strength.

III. Tropical Storm

Definition: A warm-core tropical cyclone in which the maximum sustained surface wind ranges from 34 to 63 knots (39-73 mi/hr) inclusive.

A. North Atlantic Frequency

Neuman et al. (1978) found an average of eight tropical cyclones reaching at least tropical storm strength in the North Atlantic, Caribbean and Gulf of Mexico from 1886 through 1977. The most (21) were recorded in 1933 while the least (1) occurred in 1890 and 1914. The number of tropical storms increases significantly in August, reaches a peak in mid-September and decreases towards a minimum by early November.

B. Eastern North Pacific Frequency

Simpson (1980) indicates an annual average of sixteen tropical storms in the eastern North Pacific.

IV. Hurricanes

Definition: A warm-core tropical cyclone in which the maximum sustained surface wind is 64 knots (74 mi/hr) or more.

A. Structure

Simpson (1980) describes a composite hurricane model that is based on decades of data. The storm appears as a nearly circular vortex 400 to 800 km (216-432 nmi) in diameter. The cyclonic circulation extends to 15 km (49 kft) with lower layer winds that spiral inward and accelerate towards lower pressure reaching peak speeds around a narrow ring surrounding the pressure center.

The circulation in the vortex generates the eye wall clouds and a family of spiral rain bands.

The air is forced upward at the narrow ring of maximum winds and spirals outward in the upper levels, carrying with it a canopy of cloud debris known as the outflow cloud shield.

Two circulation models are presented. The "in-up-out" model condenses inflowing water vapor that acts to warm the interior of the storm system and lower the pressure. Strong winds develop through a wind to pressure adjustment. Shapiro (1982) characterizes the earlier, formative stage by the wind field slowly developing, due in part to a weak Coriolis force, with the pressure adjusting to the wind field. The "in, down-up, down-up, out "model allows a higher degree of vertical exchange of energy, moisture and momentum in the lower two-thirds of the troposphere and is useful in examining the hurricane's mesoscale. Jorgensen (1981), in a study of five hurricanes, found the vertical profile of the eyewall to lean outward rather than straight as shown in Figures 3 and 4, suggesting a sloping updraft.

1. In-up-out circulation model

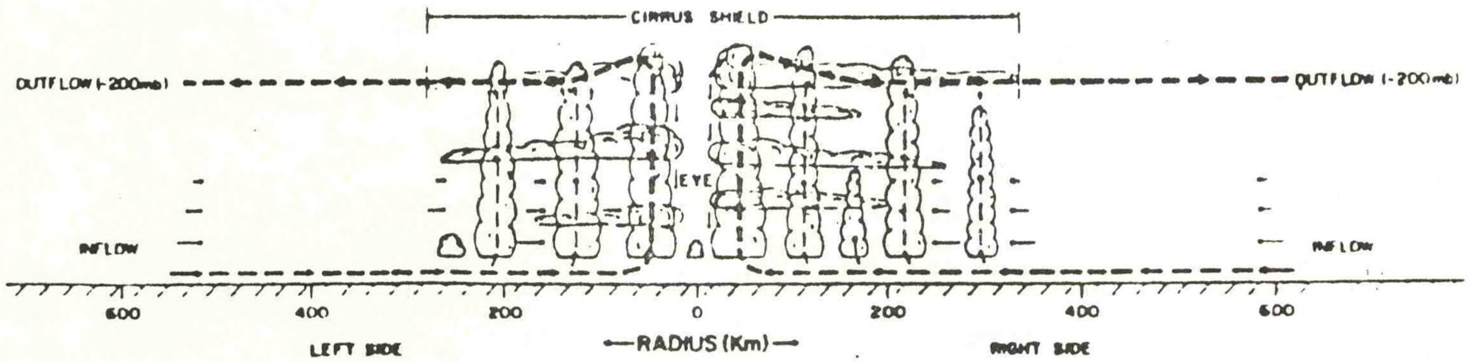

Fig. 3 Idealized view of the hurricane's mean radial circulation which is just "in-up-out" without vertical mass recycling. (After Gray, 1980)

2. In, down-up, down-up, out transverse circulation model

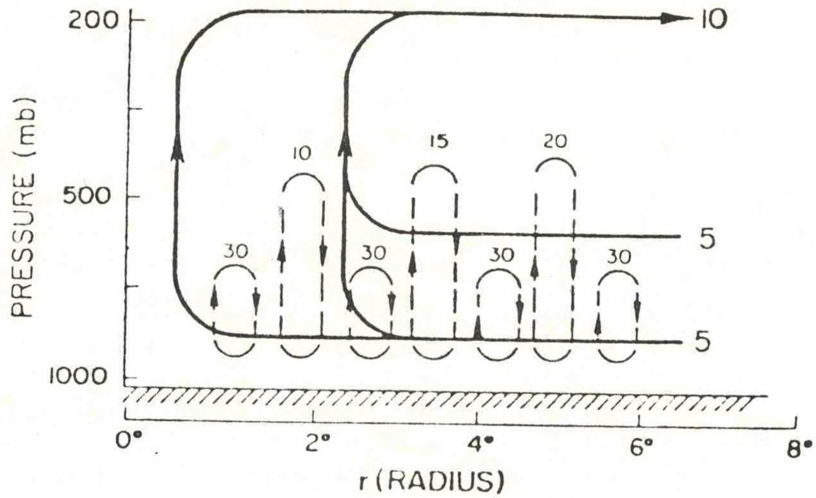

Fig. 4 Idealized cross section view of the hurricane's mean radial circulation with superimposed mass recycling. Units are arbitrary and represent mass transport. Radius values are in degrees latitude. (After Gray, 1980)

The main features of this theory are:

1. Maintenance of the hurricane's convection.

2. Raising evaporated water vapor out of the planetary boundary layer.

3. Greater tapping of the ocean energy source through downdraft drying and cooling of the boundary layer.

4. Balancing hurricane circulation against radiational cooling.

B. Energy

Energy is derived from the latent heats of condensation and fusion augmented by sensible heat fluxes from an ocean surface that is almost always warmer than 26°C (79°F).

C. Movement

Most tropical cyclones move westward 10 to 15 knots (12-17 mi/hr) to the western extremity of the subtropical anticyclone, where they tend to recurve northward.

D. Idealized radar model

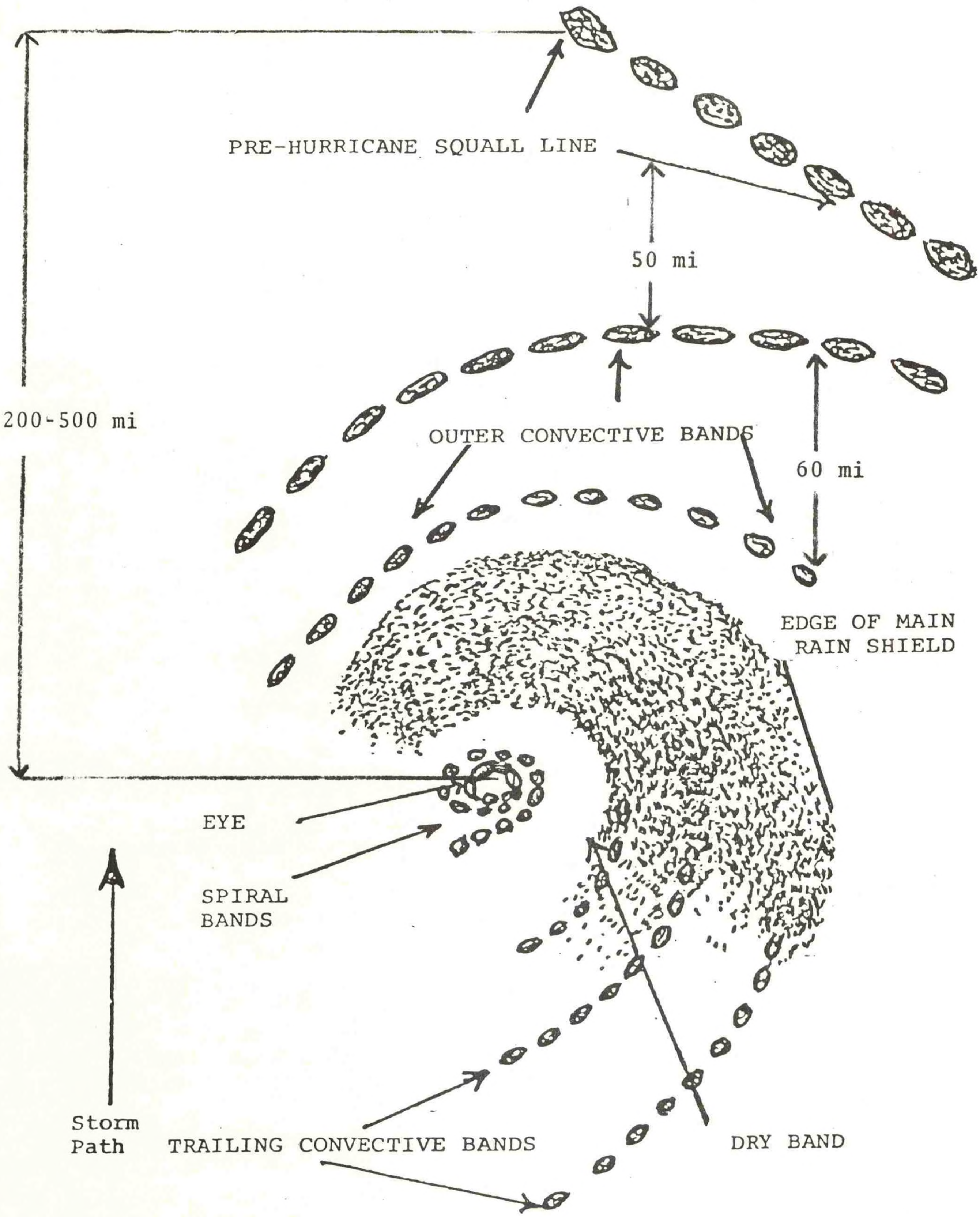

Fig.5. Idealized linear radar schematic of a banded hurricane with approximate distances.

This idealized radar hurricane model is a composite of observations made with radars operating in the linear mode. Digital video integrator processors (DVIP) began to be installed in National Weather Service coastal radars in the late 1970's and by the early 1980's all coastal radars were capable of displaying digitized intensities. The linear radar model (presented here) will undoubtedly be updated on the basis of the new digital data, but still is operationally useful. Models represent a storm average and it is rare to find a storm that precisely fits the model.

1. Pre-hurricane squall line

The pre-hurricane squall line is often the first indication of an approaching hurricane and closely resembles a squall line associated with a mid-latitude cold front. The squall line is generally straight and not organized in a spiral fashion. The pre-hurricane squall line may be separated by more than 80 km (50 mi) from the first ragged echoes of the hurricane's rings or bands and is typically a few hundred kilometers (100-200 mi) from the eye but may be 800 km (500 mi) from it.

2. Outer convective bands

Outer convective bands are composed of cells that resemble ordinary thunderstorms and have no apparent organization. There are usually two or three such bands in advance of the main rain shield with the outer most bands typically 480 km (300 mi) from the eye. Outer convective bands are usually 60 to 130 km (40-80 mi) apart.

3. The rain shield

The rain shield is a solid or nearly solid area of rain that partially encloses the storm. The outer edge is well defined, but its distance from the eye varies greatly from storm to storm.

4. Rings and bands

Willoughby <u>et al</u>. (1982) defined convective rings as annular regions of active convective heat release that encircle the centers of tropical cyclones. Convective rings are prevalent in strong, axisymmetric tropical cyclones, e.g., Allen (1980). Less intense, highly asymmetric hurricanes appear to be dominated by spiral-shaped wind and reflectivity features rather than rings, e.g., Frederic (1979). Spiral bands curve cyclonically in toward the center of the storm and appear to merge to form the wall around the eye of the storm. Near the eye they are narrow but usually become broader farther from the wall cloud.

a. Stratiform rings and bands

Jorgensen (1981) found that outside the eye wall a stratiform regime exists between active convective bands. Inner stratiform bands often have the "bright band" feature aloft characterized by 30-35 dBZ (VIP 2) reflectivity while stratiform bands in the lower layers are typically 20-30 dBZ (VIP 1). (See Appendix A for complete dBZ ranges of VIP 1 through 6.)

b. Convective rings and bands

Convective rings and bands are characterized by 35-40 dBZ (VIP 2) reflectivity or greater and at times display the "bright band" feature aloft.

With the passage of a convective ring or band over a station, the wind speed will increase by as much as 50% and there will be a sharp increase in the rate of precipitation. If tornadoes and/or downbursts occur, they are likely to be associated with convective rings or bands.

5. Wall cloud (eye wall)

The wall cloud is an organized band of convection immediately surrounding the center of a tropical cyclone. The terms wall cloud and eye wall are used synonymously. The most intense precipitation and the strongest winds are usually experienced near the wall cloud. Reflectivity from 43-45 dBZ (VIP 3) is typical.

Lewis and Hawkins (1982) observed that wall clouds often contained straight line segments along the inner edge that were aligned in a polygon arrangement.

6. The eye

Shapiro and Willoughby (1982) found the characteristic hurricane eye to form when the maximum tangential wind exceeded 35 m/s (78 mi/hr). The eye is usually a relatively calm center in the hurricane with light winds, is generally free of precipitation with clear or partly cloudy skies and is depicted by radar as an echo-free area within an eye wall that is often broken in one spot.

The radar eye diameter is highly variable, ranging from 6 to 185 km (3-100 nmi). The average diameter is about 33 km (18 nmi). Most of the time, a decrease in the diameter of the eye is accompanied by an increase in wind speed. Fujita (1980) found the shape of radar eyes to change periodically from circles to ellipses while their long axes rotated cyclonically.

a. Symmetric double eyes

Shapiro and Willoughby (1982) state that at times a concentrated ring of convection develops in symmetric mature storms outside the eye wall, associated with a secondary wind maximum. The ring then propagates inward, leading to a "double" eye wall configuration. Eventually the inner eye wall dissipates as the outer intensifies and moves inward. This cycle was observed three times during Hurricane Allen (1980).

Operationally, this means that as the outer concentrated ring of convection intensifies and moves inward the eye wall often decreases in intensity. At some point in the evolution of the new eye wall, the strongest winds and heaviest rains will occur in the outer convective ring.

Concentric rings were found to be most common in intense hurricanes, but usually marked the end of a period of intensification. The hurricane then weakened or maintained constant intensity. Once the inner eye completely dissipates, intensification may resume.

b. Asymmetric double eyes

Hurricane Frederic (1979) and Gert (1981) developed asymmetric double eye walls composed, not of convective rings, but of spiral bands that partially encircled the eye.

Surface base radar data collected by NWSTC at Slidell, Louisiana during the landfall of Hurricane Frederic showed (Fig. 6, page 12) a mesoscale eye in the northwest quadrant of the principal outer band. (Grebe, 1981)

Frederic probably represents the upper limit of intensity for hurricanes developing asymmetric double eyes.

Frederic was of special interest operationally because the winds remained above hurricane force in the large (65 km, 40 mi) echo free area within the principal outer band. A significant decrease in wind to about 30 kt (35 mi/hr) was observed only in the inner northwest quadrant eye.

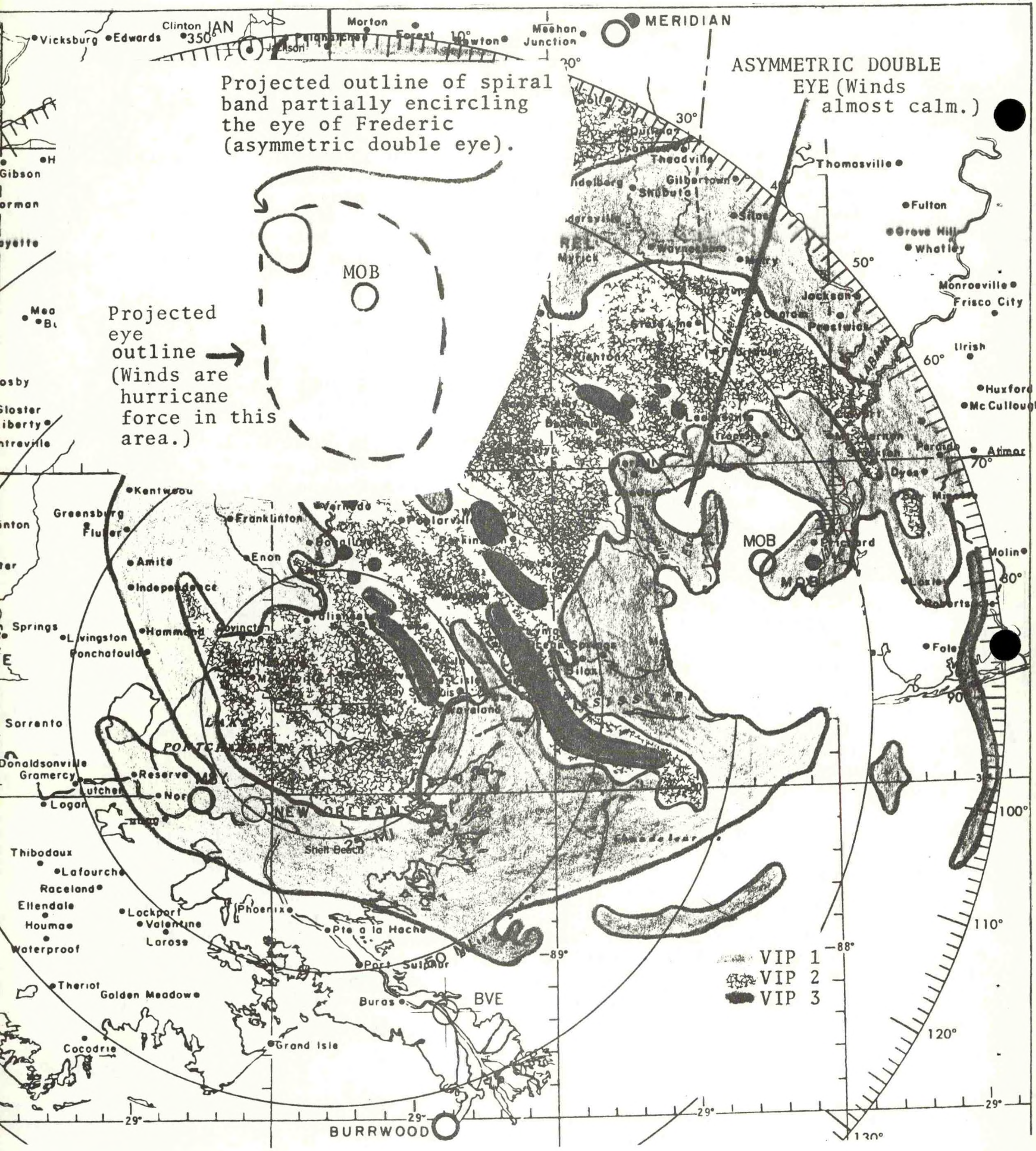

Fig.6. Radar plan view of Hurricane Frederic (1979) showing asymmetric double eye and principal outer band at 12:42 am CDT, September 13th. Range marks every 46 km (25 nmi).

c. Hurricane tracks

It is normal for hurricanes to track along an oscillatory (swinging back and forth) path rather than a smooth curved path.

Senn (1961) in an examination of four hurricanes found lateral variations in the radar eye position as great as three miles in five minutes.

Lawrence and Mayfield (1977) noted that the oscillatory motion of traveling tropical weather systems was often trochoidal and listed five contributing factors:

1. The large-scale flow pattern in which the storm is embedded.

2. Asymmetric storm features

3. Friction

4. Vertical tilt of the system

5. Storm intensity.

Trochoidal motion is described by a point on a spoke of a wheel (not on the circumference) rolling along a horizontal straight line without slipping.

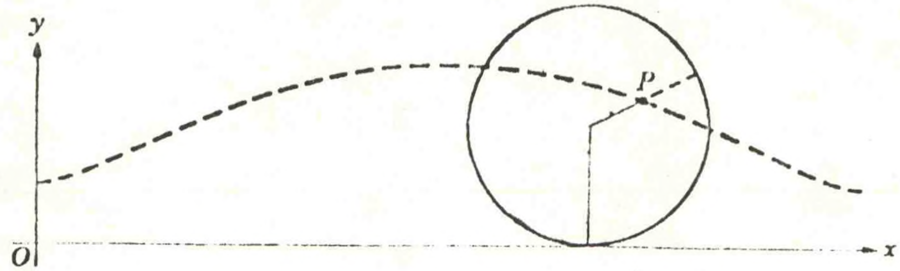

Fig. 7. Trochoid curve described by a point (P) on the spoke of a wheel.

Willoughby and Chelmow (1982) listed three methods of determining hurricane centers;

1. Dynamic center of the vortex

2. Geometric center of the eye

3. Radar observed center

and noted that research aircraft have observed centers located adjacent to the most convectively active portion of the eye wall rather than at the geometric center. Radar and aircraft data were compared for two hurricanes with small, well defined eyes that passed close to the radar at Brownsville, Texas.

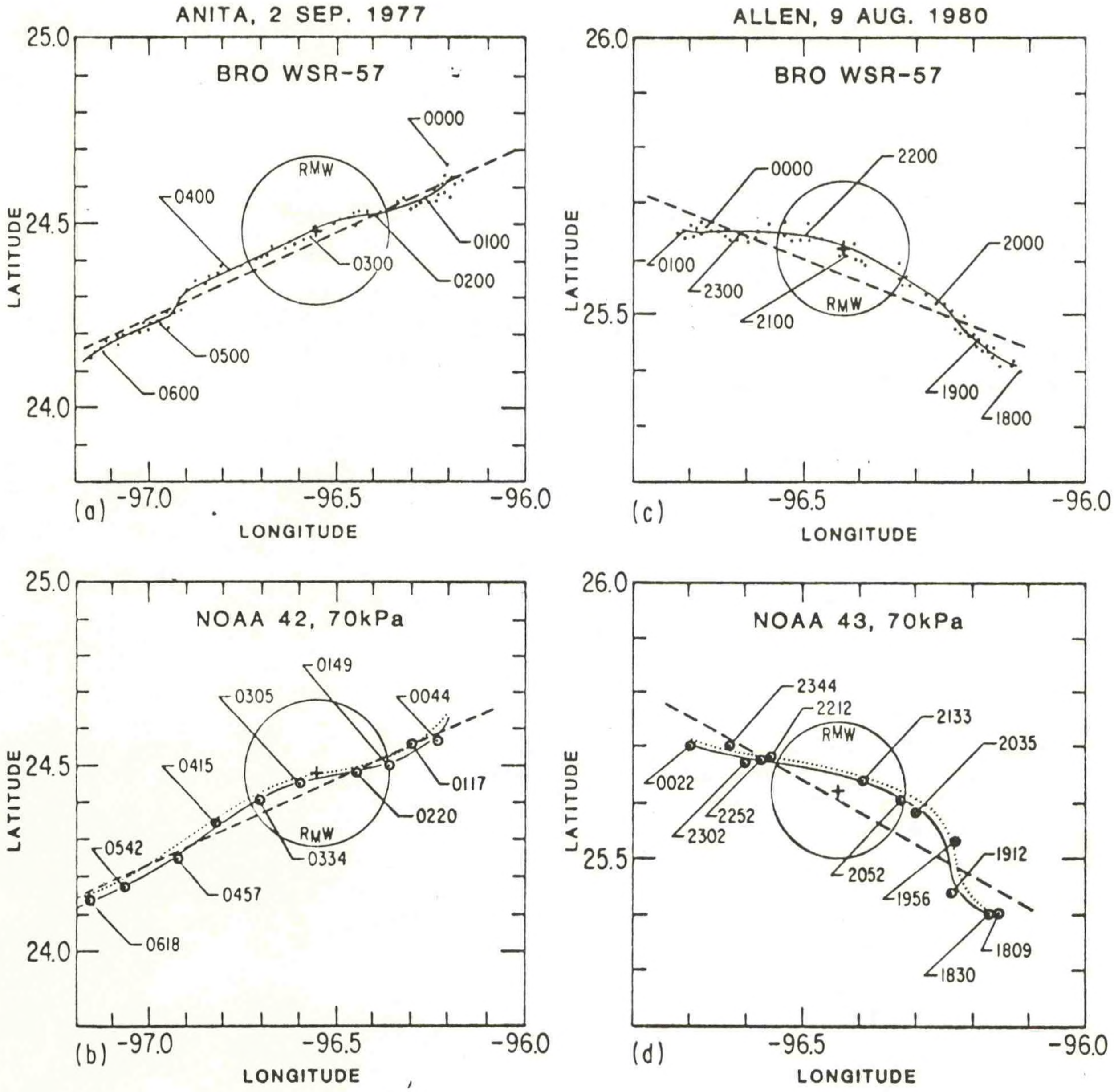

Fig. 8 Comparison between radar (a&c) and aircraft (b&d) storm tracks for hurricane Anita (1977) and Allen (1980). The solid curve is the aircraft track and the dashed curve is the radar track. Dotted curves (b&d) are aircraft relative-wind tracks determined from a coordinate system moving with the storm. The large solid circles represent the radius of maximum wind (RMW) and are centered on the radar tracks (modified from Willoughby and Chelmow, 1982)

7. Right semicircle weather characteristics

Wind and storm surge are typically higher in the right semicircle of a storm (as viewed toward the direction of motion) where the storm's motion and wind are complementary.

E. Effects

1. Wind

Over half (82) of the 138 hurricanes to directly hit the U.S. mainland during the period 1899-1980 had maximum winds ranging from 74 to 110 mi/hr (category 1 and 2). The remaining 56 were classified as major hurricanes (category 3-5).

a. Extremely severe hurricanes

Riehl (1979) noted that extreme hurricane winds of 100 m/s (224 mi/hr) have been estimated over the sea and deduced from structural damage over land. Winds in the Florida Keys hurricane (1935) and Camille (1969) are believed to have exceeded 174 knots (200 mi/hr). These were the only category 5 hurricanes to strike the U.S. mainland. (See Appendix C, page 31 for the SAFFIR/SIMPSON hurricane scale.)

b. Height of strongest winds

Riehl (1979) reported the level of strongest winds over the ocean to be about 300 m (984 ft). During landfall friction reduces the strength of the low-level winds and increases vertical wind shear while the 100 m (328 ft) winds may not be initially affected.

2. Storm surge

Definition: The height difference between the observed level of sea water and the level of sea water that <u>would</u> have occurred in the absence of the storm.

The storm surge is usually estimated by subtracting the normal or astronomic tide from the observed storm tide. The term storm tide is sometimes used interchangeably with hurricane tide.

The storm surge is a great dome of water often 81 km (50 mi) wide, that comes sweeping across the coast line near the area where the eye of the hurricane makes landfall. In general, the stronger the hurricane, the higher the storm surge for a given location. McCarthy (1982) points out that waves on top of the storm surge batter buildings and other structures along the shoreline, but tend to dampen out within 100-200 m of the normal shoreline.

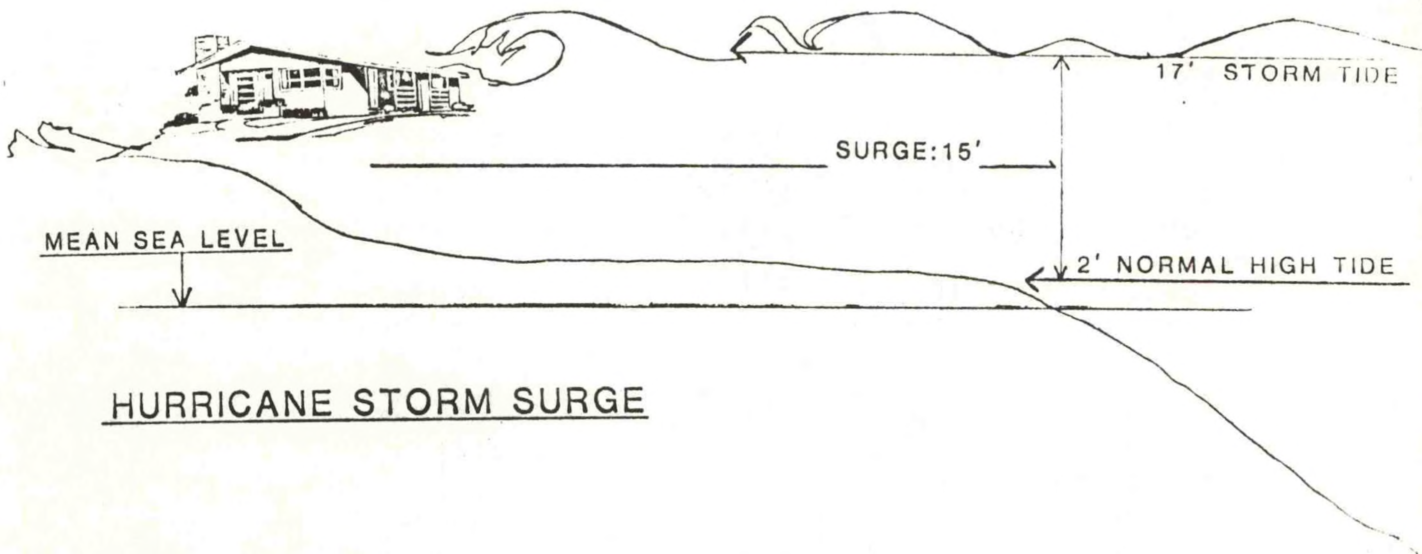

Fig. 9 Vertical cross section showing two foot normal and fifteen -foot storm surge added together to produce a seventeen-foot storm tide. Height of storm tide = height of normal tide + height of storm surge. (Diagram by C. Lester)

a. Simplified models

(1) Over water

The storm surge, over water, is dependent upon (1) the pressure drop associated with the storm (2) persistent winds blowing for several hours over distances of several kilometers (3) shorter period wind waves formed over an interval of seconds to several minutes. These forces build a mound of water that is highest under the center of the storm.

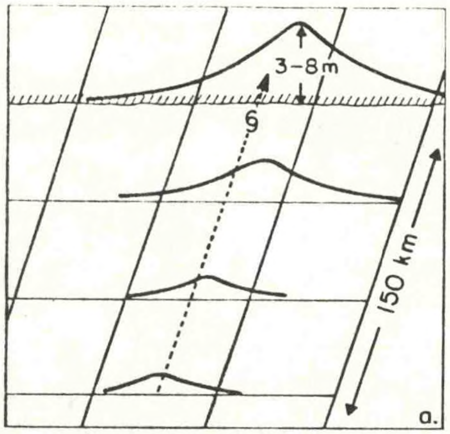

Fig. 10. Depiction of height of storm surge associated with the large-scale variation of wind and pressure at four distances from the coast. As the storm approaches the coast and the waters become more shallow, the maximum rises in sea level increase in magnitude and move from under the storm to the right of the track, reaching a maximum amplitude of 3-8 m (10-26 ft) at the coast. (after Anthes, 1982)

(2) Landfall

The angle of the hurricane's approach and local topographical features become important factors during landfall.

The greatest storm surges tend to occur to the right of the landfall position for storms moving slowly in a direction perpendicular to the coast.

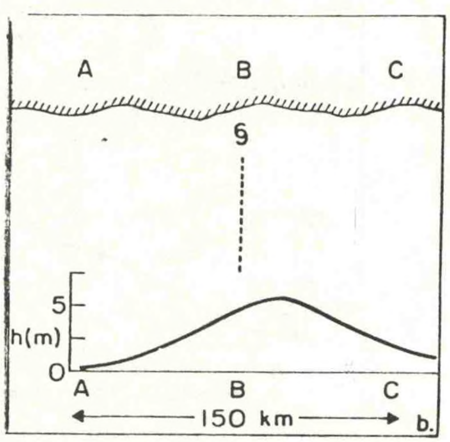

Fig. 11. Instantaneous departure of sea level for a storm moving perpendicular to the coast. (After Anthes, 1982)

The same storm moving parallel to the coast produces a smaller surge.

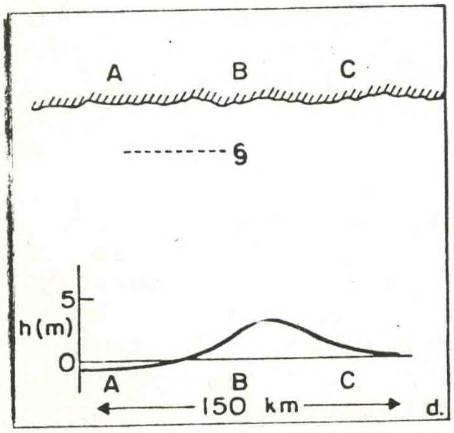

Fig. 12. Instantaneous departure of sea level for a storm moving parallel to the coast. (After Anthes, 1982)

The storm surge may double in height if the track of the storm funnels water into a bay.

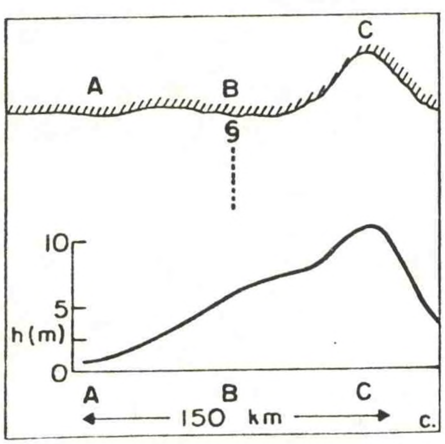

Fig. 13 Instantaneous departure of sea level for a storm funneling water into a bay. (after Anthes, 1982)

b. Astronomical tides

Astronomical tides are at a maximum around the times of *new* and *full* moon and at a minimum around the times of the *first* and *third* quarters.

spring tide: Astronomical tides that are greater than average and occur around the times of *new* and *full* moon.

neap tide: Astronomical tides that are of a minimum range and occur at the *first* and *third* quarters of the moon.

c. Danger to people

Nine out of ten hurricane deaths are caused by the storm surge.

Most of the 6,000 people killed during the 1900 Glaveston, Texas hurricane were drowned in a storm surge. Camille (1969) produced a 7½ m (25 ft) storm surge that inundated Pass Christian, Mississippi. In November of 1970, a storm surge associated with a tropical cyclone moving through the Bay of Bengal contributed to the deaths of 200,000 to 300,000 people. Anthes (1982) reported that the Bay of Bengal cyclone produced a storm surge estimated between 6 to 9 meters (20-30 ft) that occurred during landfall at almost exactly the same time as high tide. Flooding was also produced by 25 cm (10 in) of rain falling over a flat region.

3. Rainfall

Flooding can occur hundreds of miles from landfall as in Camille (1969) and Agnes (1972). Hurricane Diane (1955) brought floods to Pennsylvania, New York and New England that killed almost 200 and cost $800 million in damage. The remnants of Camille produced from 660 - 787 mm (26-31 in) of rain in just six hours over parts of western Virginia. Three years later, Agnes caused widespread flooding in the mid-Atlantic states that amounted to over $2 billion dollars. Recently, the costliest hurricanes (with the exception of Frederic) have usually been major ...flood producers. Dollar amounts associated with landfalling hurricanes need to be considered in terms of current levels of inflation.

a. Factors affecting intensity

Parish et al. (1982) list elements useful in forecasting hurricane flood potential:

1. Pattern and extent of the satellite-observed cirrus canopy.

2. Storm motion. In general, the slower the speed of the storm, the greater the threat. Neumann and Pryslak (1981) found the long-term mean hurricane speeds for the central Gulf of Mexico to be 5 m/s (11 mi/hr).

3. Orientation and height of land features near the storm's predicted path. Studies have shown that relative to storm motion, rainfall amounts tend to be maximum in the right front quadrant.

However, in Frederic, convective features that developed near the coast to the right of the track propagated cyclonically around the north eyewall where they accounted for a large part of the coastal peak in the storm-total rainfall to the *left* of the track.

b. Estimating amounts

The typical hurricane brings 152-305 mm (6-12 in) of rainfall to the area it crosses. Dunn and Miller (1960) speculated rain gages catch less than 50% of the actual rain with wind speeds greater than 25 m/s (56 mi/hr). Parrish et al. (1982) found that the storm-total rainfall estimated by radar over a 26 hour period in Frederic, using the relationship $Z=300R^{1.35}$, was within a factor of two of the true value. Willis and Jorgensen (1981) indicated that the same Z-R relationship is appropriate for estimating rainfall in hurricanes and other tropical maritime convective systems at altitudes less than 3 km (about 10 kft). See appendix A, page 29.

c. Mesoscale radar features

Radar images of hurricanes often reveal mesoscale bands that remain stationary relative to the storm. Frederic displayed bands to the north and west of the center that remained quasi-stationary during landfall.

d. Tropical storms and depressions

What was left of tropical storm Amelia (1978) dumped over 762 mm (30 in) of rain in central Texas and a decaying tropical depression produced flash floods from 457 mm (18 in) of rain in south Texas during August of 1981.

Hurricanes get the headlines, but the flash flood/flooding threat can be just as great in decaying tropical storms and tropical depressions frequently hundreds of miles from landfall.

4. Tornadoes/downbursts

In general, the more intense the hurricane before landfall, the greater the tornado threat. Conversely, the same storms tend to weaken rapidly (30mb surface pressure rise in 12 hours) after landfall.

Sadowski (1962) noted that all of the tornadoes associated with hurricane Carla (1961) occurred in the right half of the hurricane with reference to the direction of movement.

Smith (1965) in a study of hurricane-spawned tornadoes occurring between 1955-1962 found over half (55) of the tornadoes concentrated in the area between the radii at 30° and 120° from the path of the hurricane's movement and 161-403 km (100-250 mi) from the center.

Pearson and Sadowski (1965) analyzing hurricane tornadoes from 1955-1964 found the greatest concentration to be in the right front quadrant and outside the general area of hurricane force winds.

Novlan and Gray (1974) also found most hurricane tornadoes to occur in the right front quadrant relative to movement. The majority were 185 km (100 nmi) from shore. Very large wind shears between the surface and 850-mb appeared to be the most important factor in tornado genesis. Surface winds 15-20 kt and 850-mb winds 50-60 kt were typical.

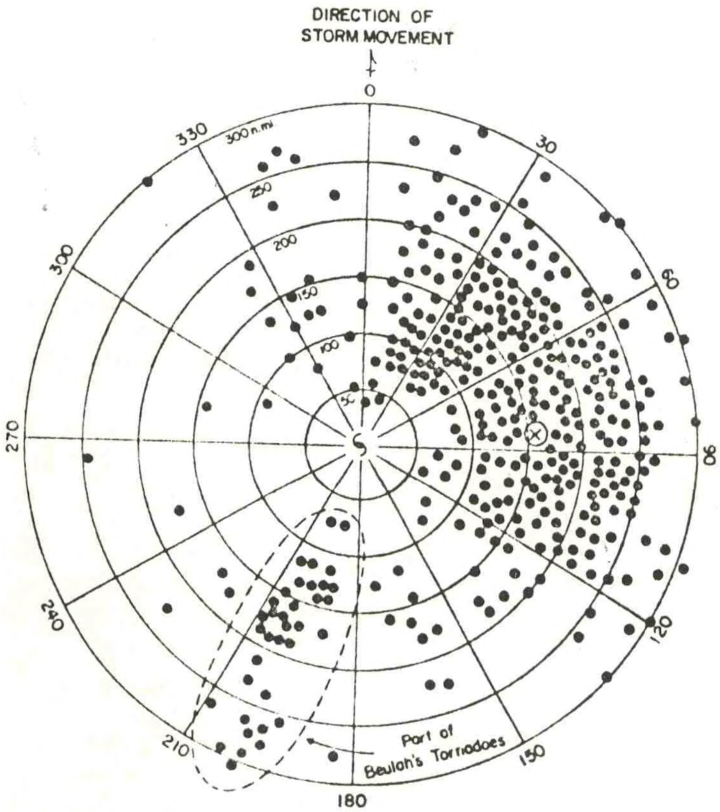

Fig. 14. Plan view of 373 U.S. hurricane tornadoes (1948-1972) with respect to the hurricane center and its direction of motion. The symbol ⊗ is the centroid point of all tornadoes, located at 80° azimuth, 150 nmi from the hurricane center. (after Novlan and Gray, 1974)

Hill et al (1966) and Fujita et al. (1972) found tornadoes are often associated with the strongest convective elements of spiral rain bands. The author speculates that the tighter the low-level radar plan view reflectivity gradient, the greater the threat of tornadoes and/or downbursts.

Phipps (1979) noted a classic hook echo on the wall cloud echo of hurricane Frederic as it moved inland on the Gulf Coast.

Purvis and Sanders (1980) in a study of hurricane-spawned tornadoes occurring in South Carolina found about 70% occurred on the north coastal plain, probably due to enhanced boundary layer convergence over sand dunes in the area.

Hurricane tornadoes are shorter lived than Plains tornadoes and tend to occur in families. Fujita (1980) in a study of Hurricane Frederic found only a few tornado occurrences and attributed most of the severe damage to *downburst* windlike phenomena associated with severe eye wall and rainband convection. Fujita explained that the damage directions were divergent by 10 to 20 degrees, suggesting that the downburst winds were superimposed on the overall hurricane circulation. For example, a 50 mi/hr downburst superimposed on a 75 mi/hr hurricane wind produces a 125 mi/hr wind. Because the wind force increases with the square of the speed, the resultant wind effect is almost three times greater than the 75 mi/hr wind alone.

Parrish et al. (1982), in a study of Frederic, found that the areas with the greatest wind damage tended to occur in regions with the highest rainfall rates.

F. Hurricane types and average forecast errors.

Crutcher et al (1980) classified hurricanes into two basic types according to movement:

1. Storms that move on a relatively steady track with no rapid or erratic changes in direction and speed.

2. Storms that go through less constrained motions.

Neumann (1981) in an analysis of Atlantic tropical cyclone forecast errors during the period 1970-1979 (Fig. 15, page 24) found that on the average, the lower the latitude of the storm, the lower the forecast error.

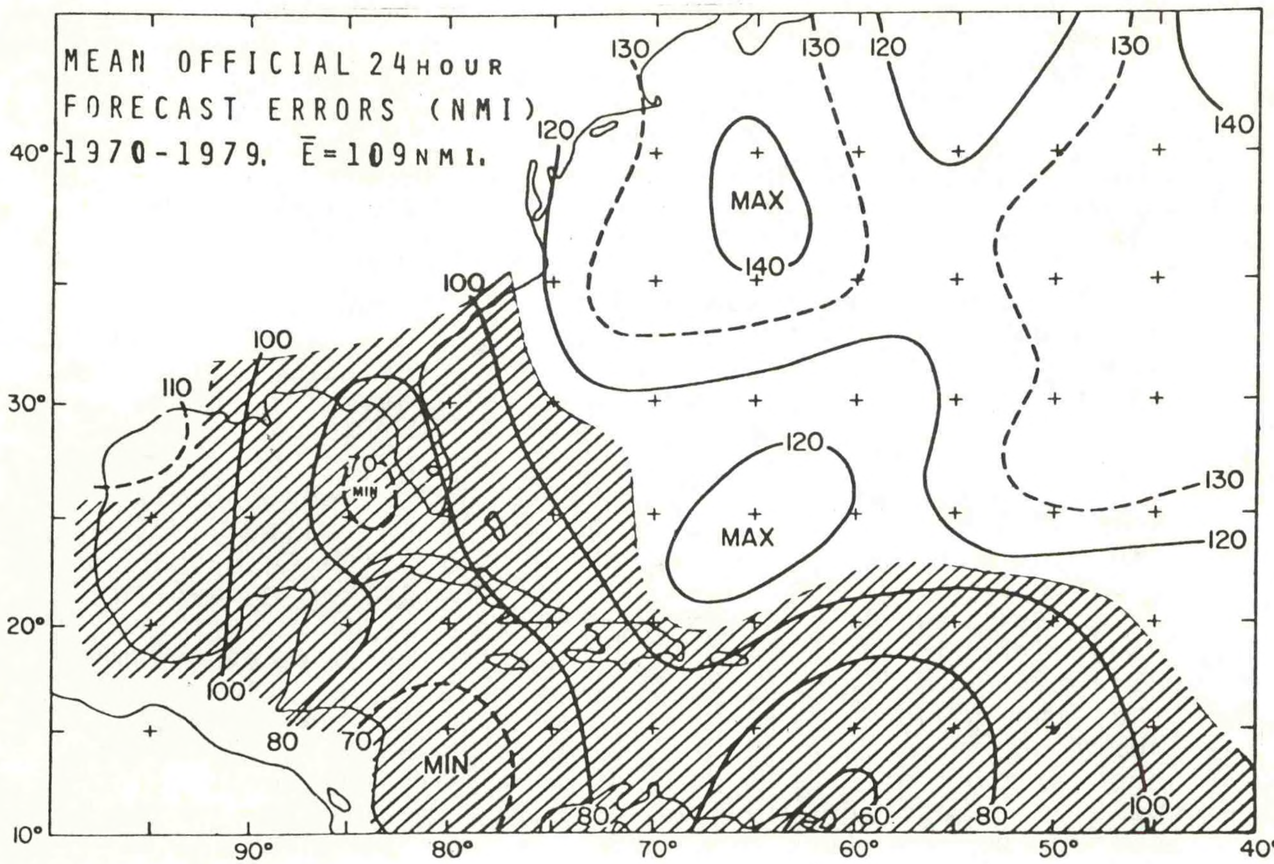

Fig. 15 Geographical variation of 24-hr mean forecast errors (mi), 1970-1979. Errors are relative to initial position of storm. Shading depicts areas where error is below average. (Adapted from Neumann and Pelissier, 1981)

SUBTROPICAL CYCLONES

Definition: Nonfrontal, low pressure systems comprising initially baroclinic circulations developing over subtropical waters.

A baroclinic circulation is characterized by horizontal temperature differences, a large vertical shear of the horizontal wind and the system being cold core as opposed to warm core. Subtropical cyclones are referred to as low pressure systems in public advisories and statements.

There are two categories of subtropical cyclones:

1. Subtropical depression: A subtropical cyclone in which the maximum sustained surface wind is 33 knots (38 mi/hr) or less.

2. Subtropical storm: A subtropical cyclone in which the maximum sustained surface wind is 34 knots (39 mi/hr) or more. Subtropical storms are referred to as storms in public advisories and statements.

There are two types of subtropical storms, each of which can evolve into a tropical storm or hurricane:

1. Cold low

   Characterized by the circulation extending from the upper troposphere to the surface with maximum sustained winds generally extending to a radius of 100 miles or more from the pressure center.

2. Mesoscale cyclone.

   Characterized by originating in or near a frontolyzing zone of horizontal wind shear with maximum sustained winds generally less than 48 km (30 mi) from the pressure center. The entire circulation of these subtropical storms sometimes encompasses an area initially no more than 100 miles in diameter. These, generally short-lived, marine cyclones, may vary in structure from cold to warm core.

WSO RESPONSIBILITIES

WSO responsibilities are current with the National Weather Service Operations Manual issuance part C, chapter 41, 5-15-81, and Operations Manual issuance, part c, chapter 41, 5-14-82.

COORDINATION OF EVACUATION ANNOUNCEMENTS

1. Coordinate your local statements with local government officials, and your Hurricane Warning Office (HWO) and/or National Hurricane Center (NHC). This helps to assure the public does not receive conflicting advice.

2. Do not hesitate to recommend evacuation if your local government fails to act or is not sufficiently organized to deal with the event.

EMERGENCY WARNINGS

You should issue local statements or warnings when warnings are not received or are inadequate to cover current or imminent conditions. If possible, contact your HWO to obtain clearance before taking action. However, if the coordination would jeopardize life or property, you need to take immediate action and then notify the Hurricane Warning Office as soon as possible.

LOCAL STATEMENTS

Numbered local statements are designed to inform the public about current and anticipated storm effects.

I. Guidelines For Initial Local Statements

A. When a hurricane watch is issued for your warning area.

B. When local precautionary actions are necessary.

Example: "Small craft should stay in port".

C. To quell unfounded rumors.

II. Philosophy

A. Local statements take the place of severe weather, special weather and flash flood statements during tropical storm or hurricane situations.

B. Local statements explain local conditions and the precautions which should be taken to minimize the storm's effect.

III. Frequency of Issuance

A. Issue at regular and frequent intervals.

B. Issue every two or three hours when a tropical storm or hurricane is near the coast, but more frequently, if needed.

C. To avoid discrepancies in public releases, local statements should not be released immediately prior to an advisory.

IV. Guidelines for Format and Content

A. Use the word BULLETIN on the line preceding the heading on all messages requiring emergency action.

B. Number the local statements and use a mass media standard text heading.

C. Write a concise "lead" sentence.

D. List watches and warnings in effect and the counties to which they apply.

E. State precautionary actions and the times by which they should be completed. This includes evacuation recommendations.

F. Give storm tide or storm surge plus astronomical tide information, including times various heights are expected, present heights and their locations, etc.

G. Tell what the present winds are and the expected time of the onset of gale, storm and hurricane force winds. Use the marine/military/aviation advisories as guidance.

H. Include any required statements on potential tornado and flash flood/flood threats, ripcurrents, beach erosion, etc.

I. Do not unnecessarily repeat information contained in an advisory that does not apply directly to your county warning area.

J. State the time of the next or final statement or that it is the final statement.

You may stop issuing local statements when the tropical cyclone and its effects (i.e., flooding, storm surge, etc.) are no longer a threat to your county warning area.

COMBINED LOCAL STATEMENT AND RADAR SUMMARY

If you issue regularly scheduled radar summaries you may choose to issue a combined "Local Statement and Radar Summary".

Always give the radar summary information at the end of the combined release.

Issue separate products if the combined product will decrease the impact and value of local statements containing evacuation information.

RADAR RESPONSIBILITY

A WSO with radar should notify NHC and the responsible HWO via RAWARC or phone whenever it observes any new developments on radar of possible interest to them.

This includes a rapid decrease or increase in the eye diameter, abrupt change in the direction and/or speed of movement, etc.

TORNADO WARNINGS

The phrase "Numerous short-lived tornadoes have been (or are) occurring.." is often appropriate for tornadoes/downbursts associated with hurricanes.

APPENDIX A

RELATIONSHIP BETWEEN VIP INTENSITIES AND DBZ VALUES

VIP	dBZ	Category	Stratiform* (in/hr)	Convective* (in/hr)
1	less than 30	Light	less than 0.1	0.05-0.2
2	30	Moderate	0.1-0.5	0.2-1.1
3	41	Heavy	0.5-1.0	1.1-2.2
4	46	Very heavy		2.2-4.5
5	50	Intense		4.5-7.1
6	57	Extreme		greater than 7.1

Stratiform table is based on the relationship $Z=200R^{1.6}$ and the convective table is based on the relationship, $Z=55R^{1.6}$ where Z represents radar reflectivity and R represents rainfall rate. The convective values for VIP 4, VIP 5 and VIP 6 have been subjectively scaled downward to account for the probability of hail.

*Official National Weather Service radar rainfall rate estimation values.

TROPICAL RAINFALL RATE ESTIMATION TABLE (See "estimating amounts" on page 20.)

VIP	TROPICAL (in/hr)
1	less than 0.1
2	0.1-0.6
3	0.6-1.5
4	1.5-2.9
5	2.9-9.6

Tropical table is based on the relationship $Z=300R^{1.35}$.

VIP 5 and VIP 6 intensities are rare in hurricanes.

APPENDIX B (Adapted from Herbert and Taylor, 1975)

TEN DEADLIEST HURRICANES, UNITED STATES 1900 - 1982

	HURRICANE	YEAR	CATE-GORY	DEATHS
1.	Texas (Galveston)	1900	4	6000
2.	Florida (Lake Okeechobee)	1928	4	1836
3.	Florida (Keys/S.Texas)	1919	4	600-900
4.	New England	1938	3	600
5.	Florida (Keys)	1935	5	408
6.	AUDREY (Louisiana/Texas)	1957	4	390
7.	Northeast U.S.	1944	3	390
8.	Louisiana (Grand Isle)	1909	4	350
9.	Louisiana (New Orleans)	1915	4	275
10.	Texas (Galveston)	1915	4	275

TEN COSTLIEST HURRICANES, UNITED STATES 1900-1982*

	HURRICANE	YEAR	CATE-GORY	DAMAGE
1.	FREDERIC (Mississippi/ Alabama/N.W. Florida	1979	3	$2,300,000,000
2.	AGNES (Florida/NE. U.S.)	1972	1	2,100,000,000
3.	CAMILLE (Mississippi/ Louisiana	1969	5	1,420,700,000
4.	BETSY (Florida/Louisiana)	1965	3	1,420,500,000
5.	DIANE (N.E. U.S.)	1955	1	831,700,000
6.	ELOISE (Florida/Alabama)	1975	3	550,000,000**
7.	CAROL (N.E. U.S.)	1954	3	461,000,000
8.	CELIA (South Texas)	1970	3	453,000,000
9.	CARLA (Texas)	1961	4	408,000,000
10.	DONNA (Florida/Eastern U.S.)	1960	4	387,000,000

* Not adjusted for inflation

** Includes $60,000,000 in Puerto Rico

APPENDIX C

THE SAFFIR/SIMPSON HURRICANE SCALE

CATEGORY	CENTRAL PRESSURE (mb)	CENTRAL PRESSURE (in)	WINDS (mi/hr)	HEIGHT OF STORM SURGE ABOVE NORMAL (ft)
	greater than or equal to			
1	980	28.94	74-95	4-5

Damage primarily to shrubbery, trees, foilage and unanchored mobile homes. No real damage to other structures. Some damage to poorly constructed signs. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorage torn from moorings.

2	965-979	28.50-28.91	96-110	6-8

Considerable damage to shrubbery and tree foilage; some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials of buildings; some window and door damage. No major damage to buildings. Coastal roads and low-lying escape routes inland cut by rising water 2 to 4 hours before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorages torn from moorings. Evacuation of some shoreline residences and low - lying areas required.

3	945-964	27.91-28.47	111-130	9-12

Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed. Serious flooding at coast and many smaller structures near coast destroyed; larger structures near coast damaged by battering waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Flat terrain 5 feet or less above sea level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.

4	920-944	27.17-27.88	131-155	13-18

Shrubs and trees blown down; all signs down. Extensive damage

CATEGORY	CENTRAL PRESSURE (mb)	CENTRAL PRESSURE (in)	WINDS (mi/hr)	HEIGHT OF STORM SURGE ABOVE NORMAL (ft)

4 (continued)

to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. Flat terrain 10 feet or less above sea level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences on low ground within 2 miles of shore.

5	less than 920	less than 27.17	greater than 155	greater than 18

Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in windows and doors. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes. Major damage to lower floors of all structures less than 15 feet above sea level within 500 yards of shore. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 5 to 10 miles of shore possibly required.

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